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SYSTEM DEVELOPMENT CORPORATION

TM-(L)-HU-033/007/00

ANALYSIS OF REQUIREMENTS FOR COMPUTER CONTROL AND DATA PROCESSING EXPERIMENT SUBSYSTEMS

ATM EXPERIMENT S-056
IMAGE PROCESSING REQUIREMENTS DEFINITION

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ATM EXPERIMENT
S-056
IMAGE PROCESSING REQUIREMENTS
DEFINITION

15 SEPTEMBER 1972

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This document was produced under NASA contract number NAS8-25471, "Analyses of Requirements for Computer Control and Data Processing Experiment Subsystems," for the Computer Systems Division of the George C. Marshall Space Flight Center's Computation Laboratory. In this report, the Huntsville Space Projects staff of the System Development Corporation presents a plan for satisfying the image data processing needs of the S-056 Apollo Telescope Mount experiment. This "Image Processing Requirements Definition" report is based on information gathered from related technical publications, consultation with numerous image processing experts, and on the experience that has been gained by the project staff in working on related image processing tasks over a two year period.

This work was performed under the technical direction of Mr. Bobby C. Hodges, Contracting Officer's Representative for the project. Appreciation is expressed to Mr. Hodges and Mr. Doug Thomas of the MSFC Computation Laboratory and Mr. J.E. Milligan of the Space Sciences Laboratory for their support and technical assistance during the course of the project.

SECTION 1. INTRODUCTION

The development of the Skylab orbiting laboratory by the National Aeronautics and Space Administration marks the beginning of a new era in space exploration. For the first time, man will be able to work in space over extended periods and thus will produce scientific data at a never before achieved rate and volume. Much of the Skylab data will be contained on the emulsion of photographic film -- largely because at present, film is the most efficient, proven means for recording large masses of data.

Previous space programs have had to deal with the special problems that occur when film is used for data storage, but no program, thus far, has been faced with the volume of data and the diversity of problems that must be expected by the designers of the Skylab experiments. Faced with such data handling problems, the designers of the Skylab S-056 experiment decided to develop a computer based system which would place a flexible, powerful, and easy to use image processing tool directly into the hands of the user of the S-056 data. This report describes such a system.

The S-056 image processing system is a hardware/software tool, centered around a large digital computer, accompanied by those special image processing devices that are required to give the user an ability for restoring distorted images, reducing their noise content, and making special measurements of the data on an ad hoc basis.

The philosophy of the design of the S-056 image processing system set forth in this report assumes that since many important characteristics of the data to be returned from space are unknown, it will be impossible to predescribe a series of image processing operations which would retrieve the maximum information from the film. The only person who could accurately dictate the required image processing operations is the astronomer himself, and even he would not know what must be done to the image until the processing was underway. Because of the need for the astronomer to make in-line adjustments, the image processing system must

include a capability for interactive control. By putting the control of the image processing operation directly into the hands of the space researcher, efficiency is increased because unwanted processing is eliminated, and responsiveness is improved because many intermediaries in the processing chain are no longer required[1]. This increase in efficiency and responsiveness will naturally lead to reduced costs because under this philosophy only those image processing operations actually desired by the researcher are carried out. The costly day-in/day-out bulk processing of frame after frame of data is eliminated.

Although the philosophy of the design of the S-056 image processing system is new, the design itself is based completely on tried and proven techniques and on well proven hardware components. The entire design is intended to provide a system that works and particular care has been taken to avoid an R&D effort in either the hardware design or software development. Every hardware component identified in this system is available "off-the-shelf", and every software technique has been proven under working conditions[2, 3, 4, & 5]. Careful attention has been given to the trade-offs between hardware and software to guarantee that system costs are kept at a minimum and that maximum capability, efficiency, and responsiveness are maintained.

Therefore, the image data processing system designed to support the S-056 experiment represents the lowest cost, most efficient, and most responsive approach that can be taken to processing S-056 experiment imagery.

SECTION 2. IMAGE PROCESSING TECHNIQUES

The techniques which are required for processing S-056 image data have been identified, tested, and developed over a period of some eighteen months. A five month's study (October 15, 1970 - March 15, 1971) identified some of the more important technique requirements, provided illustrative software designs, and evaluated each technique with respect to its usefulness in support of the experiment and its computer requirements. The results of this effort were reported in SDC Technical Memorandum (TM-(L)-HU-033/004/00) dated March 15, 1971[6]. Subsequent one-year development efforts provided a prototype image processing software system called IDAPS, identified and developed additional, applicable image processing techniques, and applied the developed techniques to real image data to prove out the design and give the project team valuable, practical experience. The computer software which was developed during this period represents a prototype design for approximately one third of all those routines needed to process the S-056 images and the techniques investigated can satisfactorily carry out all known, required image processing operations. The results of that effort were contained in SDC Technical Memorandum (TM-(L)-HU-033/005/00) Volume I and II, dated March 15, 1972[7].

On the basis of the preceding efforts, it is now possible to identify specific image processing technique design objectives for supporting S-056 experiment data handling needs. From these objectives, requirements for computer system and applications software may be derived, and pertinent characteristics of computer and peripheral hardware projected. Figure 2-1 presents the S-056 image data processing technique design objectives in graphic form. Hardware and software design requirements are discussed in the sections which follow.

The technique design objectives listed in Figure 2-1 have been categorized into a number of classes of applicable techniques. Although these techniques (linearization, noise removal, etc.) represent the specific image processing

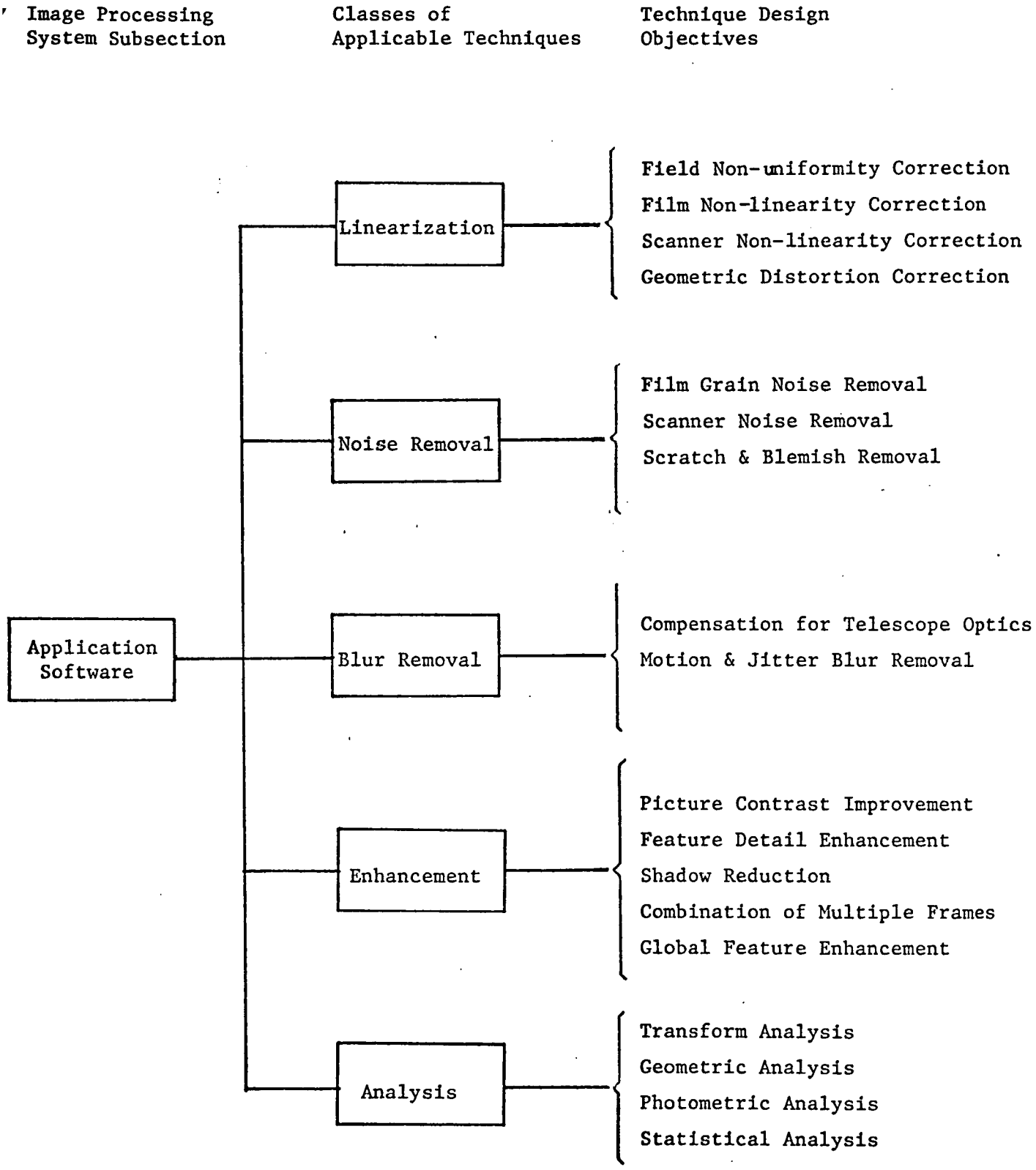


Figure 2-1. S-056 Image Data Processing Technique Design Objectives

application software requirements of the S-056 experiment, within them may be found applications to many other experiments as well. This design generality is deliberate since it is desirable to produce a system which not only satisfies the immediately identifiable needs of the S-056 experiment, but which is flexible enough to accommodate new requirements as they occur.

In order to appreciate the usefulness of the proposed system in processing S-056 image data, an understanding of the purpose and approach anticipated for each technique is helpful. Worksheets have been prepared which briefly outline the purpose and methodology of each technique, and point out the needs for any special hardware or software items. These worksheets are included as Appendix A in this report.

SECTION 3. HARDWARE

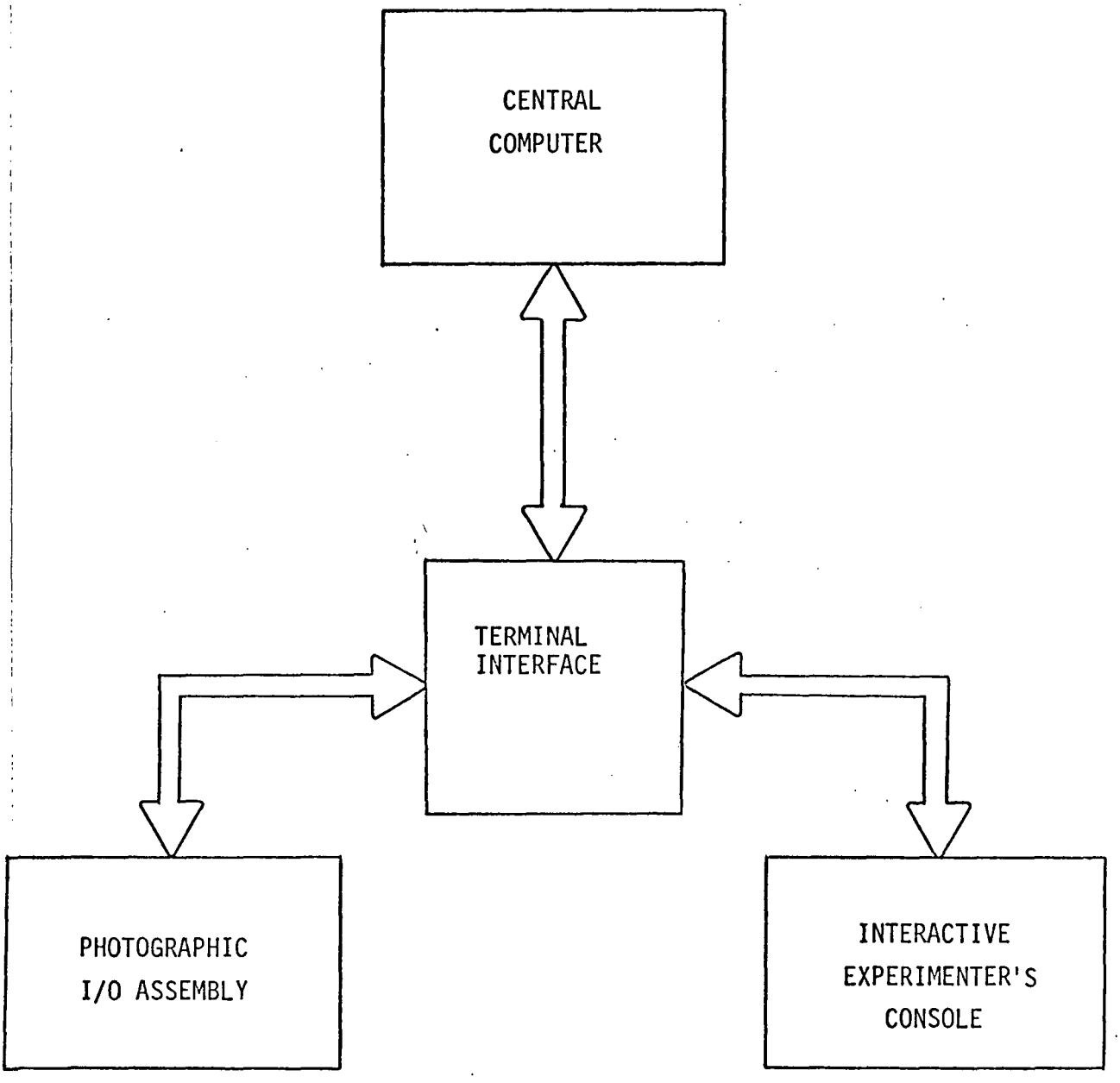
The processing of data in an image format requires the introduction of unique components to the normal data processing facility. One outstanding requirement of the image processing facility is the necessity of being able to convert photographs from film format to digital data arrays, and to reproduce the processed data arrays as pictures on the face of a CRT device or as hardcopy photographs. Another important requirement of the facility is to provide a capability for identifying specific data points within a large array of numbers without having to address each number in the array in a sequential order. These and other factors, peculiar to handling image data, dictate a unique set of requirements for the design of a computer based facility for processing image data.

In the case of the S-056 experiment, additional consideration must be given to the fact that no specific computer has as yet been selected for processing the S-056 image data. Because of this, hardware interfaces between the central computer and any image processing peripheral devices must be kept to a minimum and those interfaces which must be established, should be given careful consideration to assure a minimum cost and time loss in system integration. Also, the problem of providing software which is relatively independent of the choice of central computer hardware, requires that all possible programs be written in a universal computer language.

The selection of the hardware necessary to support the image processing needs of the S-056 experiment is based on a careful and exhaustive study. Numberous trips have been made to existing image processing facilities throughout the country, available sources of documented information have been researched, and personal contacts with other people, familiar with the problem of image processing, have yielded valuable information about those hardware devices and features which are needed in an image processing facility.

The general configuration of the hardware which is needed to Support S-056 image processing is presented in Figure 3-1 as four major assemblies:

- Central Computer
- Interactive Experimenter's Console
- Photographic I/O Assembly
- Terminal Interface



GENERAL HARDWARE
CONFIGURATION

Figure 3-1

3.1 CENTRAL COMPUTER

The Skylab S-056 experiment is expected to return some 20,000 35mm. photographs, and the resolution capability of the S-056 optics will resolve detail down to at least five microns[8]. This means that each image frame will produce sixteen million 8-bit numbers or that the experiment will produce 256×10^{10} bits of data. Even if, by putting the astronomer in the processing loop, the actual data which must be processed can be reduced to a fraction of this huge figure, it is still obvious that a computer with a capacity for handling large masses of data must be employed.

Interactive computer processing automatically implies responsiveness and speed. Putting a man "on-line" means that the central computer must be able to process image data at a rate which is fast enough to maintain his attention and not destroy his thought processes. This means simply that when the S-056 experimenter desires attention from the central computer, he should not have to wait for long periods of time while other jobs are being completed and once he has entered a job, the response should be prompt enough that he does not become impatient. Therefore, the interactive experimenters console must be assigned a high priority under the operating system of the central computer, and the computer hardware must be configured so as to recognize that priority and respond quickly.

3.1.1 Central Processor Characteristics

No specific determination of minimum computer size or speed can be made for a particular job mix without mentioning the peculiar characteristics of a single manufacturer's product. It is most often the unique characteristics of his machine that the computer manufacturer points to in making his claims of a superior product. It now is possible to specify the make, model, and configuration of a specific computer which can satisfy the S-056 image data handling needs, but this would not be fair to the other manufacturers, and so, a more general approach for defining the characteristics of the central computer has been taken.

The central computer should have at least 65K words of high speed core with a minimum word length of 32 bits, and should be byte (or at least half word) addressable. Preferably, the byte should consist of eight binary bits since this corresponds to the 256 levels of gray that will define most of the image data being processed. The computer should possess hardware logic for doing fixed or floating point arithmetic with a single precision accuracy of at least seven decimal digits. The entire memory should be directly addressable within the primary instruction word, without the need for base registers.

Typical operating times for responsive operation of the central computer are based on the assumption that a user, applying an operator which consists mainly of add's and multiplies to a 256 X 256 image array, should not have to wait more than 20 seconds for a reply. The memory cycle time should not be more than one microsecond and a single precision, floating point add should require not more than four microseconds and a multiply should require no more than six microseconds.

The central processor should have the capability of supporting programs in a multiprogramming mode; e.g., handling batch applications as well as inquiries from remote terminals.

The central processor should provide an interrupt system, coupled with a suitable buffering scheme to effect data input without appreciably degrading the processor's performance. As a minimum, interrupts should be initiated by program errors, equipment errors, I/O servicing, time clock interrupts, or the remote console. The computer should be capable of sustaining the required interrupts simultaneously, at multiple levels, without losing interrupt requests or status information.

Due to the nature of the image data files which must be handled, the responsiveness of the central computer will probably not be determined by its CPU cycle rate, but by the time taken to access data within a file. Since it is unlikely that entire files can be stored in core, the ability to address,

retrieve, and store individual records assumes extreme importance. This dictates that a high speed disk or drum be coupled to the computer core through sufficient data channels to assure that the transfer of data is not interrupted by the transfer from some other device and that it in turn does not interrupt central processing once the transfer is initiated.

3.1.2 Peripheral Device Characteristics

A number of standard peripheral devices are required as part of the central computer to support the image processing needs of the S-056 experiment. These devices are required to support the day-to-day operation; provide adequate I/O for software design, installation, and maintenance; and provide appropriate means for communicating with other image processing systems or with various, unattached devices within the system.

The central computer should have the following peripheral devices:

1. High speed Diak
   - at least 8.0 million 8-bit bytes.
   - average access time $\leq$ 20 ms.
   - transfer rate minimum 250K bytes/sec.

2. Removable Disk File
   - at least 50.0 million 8-bit bytes
   - average access time $\leq$ 100 ms. (including rotational latency)
   - transfer rate minimum 300K bytes/sec.

3. Tape Drive
   - minimum of 3 units
     1-7 track, 2-9 track
   - up to 800 bpi capability
   - 1/2" tape, 2400 ft. reels

4. Card Reader
   - 600 cards/minute minimum
   - intermixed binary and EBCDIC decks

5. Card Punch
   - 300 cards/minute minimum
   - either binary or EBCDIC decks

6. Line Printer
   - 65 character character set
   - 132 print positions/line
   - 600 lines/minute minimum

7. Digital X-Y Plotter
   - on-line
   - max speed at least 2 in/sec.
   - resolution of 0.01 in./smallest increment
   - plotting mode - incremental
   - symbol printing
   - medium-ink
   - size at least 12" X 12"

3.2 INTERACTIVE EXPERIMENTER'S CONSOLE

It has been previously pointed out that the image data processing for the S-056 experiment must be an interactive process. This means that the S-056 experimenter must be able to input a trial run and receive the processed results in a time frame that is short enough that he will not be discouraged by the delay. The philosophy of operation is such that, once the desired image processing procedure has been developed through the interactive trail-and-error process, it can be applied to larger data formats in the more conventional batch mode. That is, the experimenter

works with a small piece of a picture until he is satisfied with the results of the process and then he can switch from interactive to batch operation to process the bulk of his data.

An interactive experimenter's console has been included in the design of the hardware system to provide the display and control responsiveness required for interactive processing. This console, (see Figure 3-2) accompanied by the proper software, provides a means for an experimenter, unfamiliar with computer programming, to set up, initiate, and control trial processes and to develop procedures for handling specific image data processing tasks. The major components of the console are:

- TV Displays
- Display Refresh
- Video Control
- Graphic Input Devices
- Special Function Panel
- Keyboard/printer
- Card Reader

3.2.1 TV Display

Sufficient television display capacity should be provided in the interactive experimenter's console to allow the simultaneous presentation of two black and white pictures and one color picture. Each of the black and white pictures should be presented as a 256 X 256 element array with at least 32 levels of intensity. The frame size for the black and white tubes should be from 8 to 10 inches on the diagonal. The color display should be a standard shadow mask tube of from 12 to 19 inches diagonal dimension. Each of the three color guns should be capable of presenting a 256 X 256 array of values at a minimum of 32 levels of intensity. Refresh rate should be a standard sixty frames per second interleaved. The ability to

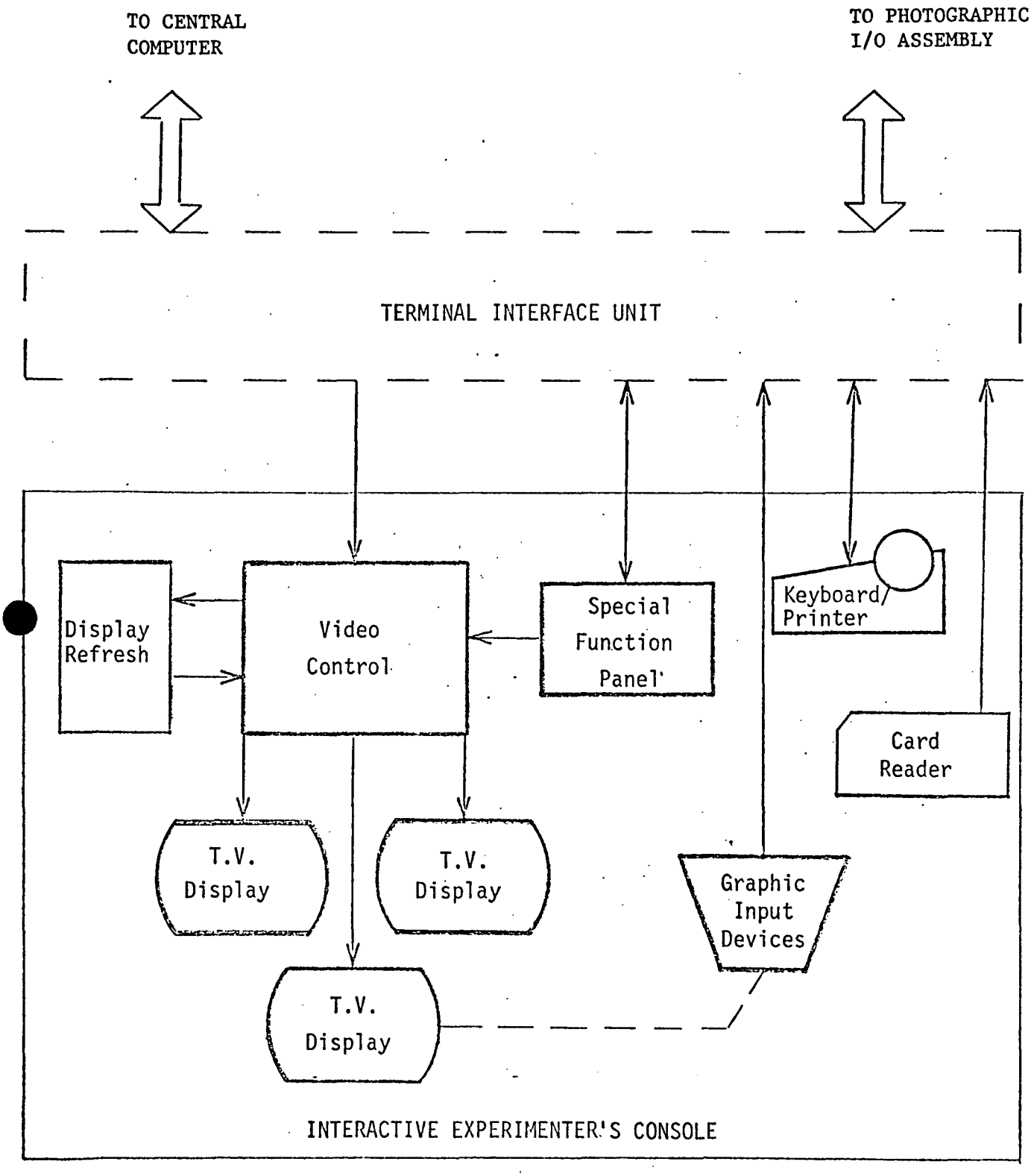


Figure (3-2) Interactive Experimenter's Console

accept a full 512 X 512 array is a desirable but not necessary feature. Overall geometric and luminescent linearity should conform with the highest standards of commercial television presentation.

3.2.2 Display Refresh

Due to the number of displays, the size of the format, and the level of accuracy required, a substantial amount of random access memory is needed to refresh the screens. To display 32 levels of gray on the black and white TV's and 32 levels on each of the three colors on the color TV will require 256 X 256 X 25 bits of data storage. Allowing one 256 X 256 plane of bits per display gun for superimposing line graphics, the total requirement is 30 bits for every picture element position. That is, based on a frame size of 256 X 256, the total refresh storage required is approximately two million bits. A number of possible means of display refresh have been investigated including high speed disk, drum, core, and storage tube. When the factors of cost, reliability, performance, and availability are considered, the high speed disk appears to offer the best solution to the problem of display refresh. Also, with proper logic and switching, and some additional capacity, the refresh memory can serve as a storage device for data frames between processing runs.

3.2.3 Video Control

The video control unit provides for the flexible and efficient use of the proposed T.V. Displays. It allows the operator to assign a picture or line drawing to any of his display electron guns. Thus, for example, it is possible for the experimenter to draw a red border around a solar feature, displayed in color on the shadow mask tube, transfer that border to one of the black and white displays, and continue processing on the border data in black and white. This also allows the side by side comparison of four

pictures with a fifth picture in black and white by consecutively switching comparison frames onto one black and white tube while holding the reference frame on the second tube.

3.2.4 Graphic Input Device

A major problem in image processing is the designation of specific features of a frame of data to the computer. For example, it may be desirable to describe to the computer the outline of an irregular shaped, fuzzy object. Such a description could require the keyboard input of the location of every point of data along the outline. Various devices have been developed to simplify this process including light pens, trackballs, acoustic pens, joy sticks, data tablets, etc. Of all the devices evaluated, a pen-type device seems to be the most natural means of entering such data. A graphic pen, operating on an acoustic principle, has recently been developed which can be attached to a television monitor in such a way that it can be used directly on the face of a TV display and thus the user has very accurate control of the cursor position. Such a device is recommended for use in the interactive experimenter's console. As a backup to this device and also to allow the operator to "back away from his work", a track ball, "mouse", or joy stick should also be included.

3.2.5 Special Function Control and Display Panel

The purpose of the special function control and display panel is to simplify commonly performed operations by presenting the experiment with simple switch actions for control and indicator lamps for feedback. The panel should contain the following:

- Thumbwheels to control cursor X and Y position
- Digital indicators to indicate cursor X and Y position
- Thumbwheels for cursor X and Y dimension
- Toggle or rotary switches for cursor on, off, blinking
- Toggle switch to control cursor gray scale

Position 1 - cursor gray scale = inverse of gray values of element

Position 2 - cursor gray scale = thumbwheel setting

- Thumbwheel to set gray scale value of cursor
- Switch (5 way) to direct cursor information to one of the black and white displays or to one of the three color guns
- Switch (4 way) to assign cursor control to thembwheel, graphic pen, track ball, or to incremental stepper
- Digital indicator to indicate gray value of the picture point located by cursor
- Switch for cursor retention or non-retention
- Switch for permanent or temporary gray scale modification
- Up, down, right and left cursor incremental stepper control buttons.

3.2.6 Teleprinter

Alphanumeric communication between the interactive experimenter's console and the central computer will be via a teleprinter. The teleprinter will be used to specify operators and parameters to the computer and to provide tutorial aids to the experimenter as well as providing a running record of the sequence of operations performed.

3.2.7 Card Reader

In order for the experimenter to input a predetermined sequence of operations from the experimenter's console, a low speed card reader is included. This card reader should be capable of reading at least 100 cards per minute.

3.3 PHOTOGRAPHIC I/O PACKAGE

The data obtained by the Skylab S-056 experiment will be returned to earth on photographic film. The money and time involved in preparing and flying the S-056 experiment makes this data extremely valuable and consequently, the extraction of the data from the film must be carried out with the utmost

care and precision. Once the film has been converted to digital data and expensive computer processes have been applied, the criticality of presenting the processed data to the scientific researcher is compounded. By this time, not only is the expense of the experiment itself involved, but the cost of the data processing as well.

Therefore, throughout the entire image data processing operation, from the minute the film canisters are opened for development until the processed data is presented to the analyst the utmost care must be maintained not to lose any of the information content of the film or to distort the data in any unplanned way. In this light, the importance of accurate film scanning and data display can be appreciated.

The diverse requirements of the S-056 experiment dictate a somewhat redundant approach to both film scanning and redisplay. The following discussion describes the need for both slow speed, extreme accuracy scan and display devices as well as for higher speed equipment in which the accuracy and resolution are somewhat reduced.

3.3.1 Scanners

The scanners used for converting film data to digital/electrical data may be classified in a number of ways. First, there is the mechanism for holding the film while it is being scanned (a flat table or a rotating drum). Then there is the scheme used for moving the light source relative to the film (the light may be stationary and the film moved, the film may be stationary and the light moved, or both the film and the light may be moved in different directions). And there is the pattern of the path traced by the light beam on the film (in a spiral or helical path starting at the center, in a raster or left-to-right/right-to-left fashion, or in a uniform left-to-right only pattern which requires the light to return to the left edge at the end of each line). Finally, there is the source of the light itself (tungsten,

laser, and electroluminescent light sources are all commonly used in film scanners). Each of these characteristics have their own advantages and disadvantages, and they may be put together in a number of ways to satisfy specific needs. Two specific film scanning needs are addressed in relation to the S-056 experiment.

- A high speed, moderate resolution, easy-to-use and versatile scan device is required for the day-to-day conversion of film to digital data.
- An extremely high resolution, high accruacy, moderately fast scanner is required for the conversion of high interest portions of the film data.

3.3.1.1 High Speed Scanner - The following characteristics describe the high speed scanner which will be used on a day-to-day basis for converting S-056 films to computer processable data:

- Effective scanning aperatures from 10 to 100 microns should be provided with row and column separations so that scan lines may be edge-to-edge or overlapped.
- A sensitivity to measure film densities from 0.0D to 3.0D with a minimum discernability of no more than 0.02D. The measured density levels should be quantized to 256 gray scale values or 8 bits binary.
- The X and Y position repeatability should be no greater than $\pm$ 1 micron, and the X and Y straightness of travel should deviate no more than 1 micron/mm.
- The scanning rate should be fast enough to scan a 512 x 512 sample array with a 50 micron spot in less than one minute.

- An automatic film transport should be provided to handle rolls of 35mm film and to advance or rewind the film between scans.
- Photometric linearity should be such that a quantizing error no greater than .02D should be experienced as a function of scan position.

3.3.1.2 High Resolution Scanner - In order to extract maximum information from high interest areas on the S-056 film, an extremely high resulution scan device is required. The extreme precision required of this scanner dictates a coherent light device which has the following capabilities:

- Minimum effective spot size of one micron
- A recording density range of 0.0D to 3.0D
- A quantization resolution of 256 density levels (8 binary bits) with a stability of better than 0.02D
- X and Y axis repeatability should be at least $\pm$ 1 micron
- X and Y straightness of travel should be within 0.1 micron per mm.
- Should scan 35 mm film at a rate which would convert a 1 mm^2 area to a 1000 x 1000 array in less than ten minutes.

3.3.2 Photo-Hardcopies

Even though much of the information prepared by the data processing of S-056 films will be presented in printed or graphic form, the bulk of the output of computer processes will still be pictoral information and must be returned to picture format for analysis. The television displays described in Section 3.2.1 are adequate devices for viewing picture data during intermediate steps of the interactive processing of the data, but for final output of the results, a hardcopy print must be produced. Two levels of photo-hardcopy have been identified as hardware requirements of the S-056 image processing system -- a high speed device for making copies for general viewing and for intermediate

picture storage, and a high accuracy, moderate speed device for producing photographic hardcopy with high geometric and photometric accuracy.

3.3.2.1 High Speed Photo-Copier - A high speed hardcopy device is needed in conjunction with the S-056 image data processing interactive experimenter's console to provide a quick and easy means of obtaining photographic prints of image data arrays which are stored in computer memory. The following characteristics are required:

- The capability of producing polaroid prints, 35mm slides, and 16mm movie frames through the interchangeability of cameras.
- Complete remote control to allow shutter trip and frame advance from the interactive experimenter's console.
- The ability to expose the above films to a minimum of 32 density levels spread uniformly across the linear portion of the recording film's characteristic curve.
- The ability to record a 512 X 512 picture array at 32 levels of gray in less than one minute.
- A position/gray scale linearity of no worse than one gray scale step variance between any two points on a picture for any constant value input array.

3.3.2.2 High Accuracy Photowriter - A highly accurate device is required for providing photographic output from the S-056 image data processing system in those cases where photometric accuracy are critical. The following characteristics are required:

- The ability to expose photographic film with a modulated spot of light which is adjustable from 10 to 100 microns diameter.

- The ability to modulate the exposing light beam in such a way as to utilize the full film latitude and to produce a total of 256 density values on the film, spread linearly over that film latitude range with a deviation of no more than $\pm$ 1/2 gray scale value (assuming a linear film characteristic).
- A positioning accuracy of at least 1 micron and an X and Y straightness of travel deviation of no more than 1 micron/mm.
- A photowriting speed which will expose a 1024 X 1024 array of numbers to a 50 micron spot in less than ten minutes.

3.4 TERMINAL INTERFACE UNIT

Because the S-056 image processing system must be capable of being implemented on any of a number of large scale computers with a minimum of cost and complexity, a special interface unit has been included in the design to act as a central interface point for those hardware devices which are peculiar to the S-056 needs and which must have access to the central computer. By incorporating this unit into the design, it is possible to greatly reduce the problems commonly encountered in interfacing a number of non-standard terminal devices with a large scale computer.

The terminal interface unit performs a number of important functions in the system:

- Data Collection and Format Control
- Data Communication Control
- Interactive Display Sequencing & Control
- Special Logic for Display and Control

3.4.1 Data Collection and Format Control

In order to form an effective bridge between the various image processing terminal devices and the central computer, the terminal interface unit must provide a compatable interface between itself and each of the terminal devices.

Such factors as switching levels, transfer rates, data formats, interrupts, timing and sequencing must all be accounted for in the interface unit design. Suitable buffering must be provided for all terminal devices to assure a maximum data handling efficiency while guaranteeing that no valid data is lost. Appropriate logic for reformatting the data should be included as necessary for efficient communication between terminal devices and the central computer.

One particularly important feature of the terminal interface unit is the ability to translate the user language provided as input to the image processing software system. This means that the instructions provided by the user in the user language are translated into a form which can be recognized by the operating system of the central computer.

3.4.2 Data Communication Control

By providing an interface between itself and all image processing terminal devices, the terminal interface unit reduces the number of central computer interface points to a single, high speed link. This link should be constructed so that data transmission to the central computer from a terminal device is initiated by an interrupt or input code from the device and continues with the signaling of the central computer by the terminal interface unit through a central computer interrupt. Once the central computer has provided a suitable memory space for storing the data, it signals the terminal interface unit that it is ready for transmission of data, whereupon, the interface unit inserts data into the data stream for transmission to the computer. A transmission rate of at least 200 kilobaud is required for efficient terminal/computer communication. Data transmission from computer to terminal device follows much the same pattern, utilizing such buffers as needed in the terminal interface unit to insure a smooth data flow.

When communicating in either direction, the terminal interface unit provides the encoding, decoding, sequencing, and synchronization necessary to minimize the terminal/computer interface problems.

3.4.3 Interactive Display Sequencing & Control

The terminal interface unit provides the special logic needed to control storage and display of pictoral data on the interactive experimenter's console T.V. monitors through the T.V. refresh memory. To do this, the interface unit collects data arrays, formats them for storage, assigns the data to proper refresh memory channels, and transmits the data to those channels. The interface unit also performs the necessary logic to superimpose such graphics as borders, cursors, grids, and labels onto the pictoral data being displayed. If the refresh memory is used as an intermediate data store for data arrays, the terminal interface unit retrieves requested arrays from the refresh memory, and reformats it for transmission to the central computer.

3.4.4 Special Logic for Display and Control

The terminal interface unit performs the logic and switching functions needed to operate the Special Function Display and Control Panel (see Section 3.2.5).

SECTION 4. SOFTWARE

An extensive array of software is necessary to support the image processing requirements of S-056. Some of the factors contributing to the magnitude of the software job are:

- The experimental nature of the S-056 mission,
- the varied non-standard hardware devices such as interactive experimenter's console, scanner, cameras, etc.,
- the interface between the terminal interface unit and central computer,
- the system approach that is being taken to integrate all software into a single package,
- the concept of making the system user oriented to the extent that all the facilities of the system are available to the non-programmer.

4.1 LANGUAGES

Several languages are required to program the image processing system for S-056. These languages may be divided into two basic classifications:

- User Language
- Programmer Language

4.1.1 User Language

Since the ultimate users of the system are not programmers per se, a means of communicating with the system must be devised which is easy to use, yet powerful enough to accomplish the desired set of tasks. The language designed for the user must be efficient and succinct. It need not be English-like, but should be oriented to a class of user who is technically trained in image processing. Such a user is interested in accomplishing a task quickly and efficiently and thus is willing to accept artificial conventions and short-cuts which save him time and effort. It should be stressed, however, that the user must not only bring his own skills to bear on his particular problem, but must also master the capability of the system.

The dichotomy of the IDAPS user language, as well as any user oriented language, is that flexibility and ease of use do not necessarily go hand-in-hand. To construct a language that is easy to use implies a limited set of capabilities, a minimum number of options, rigid formats and fixed sequences of operations leading to a desired end. Such a language does not provide the flexibility required in an R&D type setting. On the other hand, a very flexible language that demands a great deal of sophistication and training on the part of the user will not be used for the very reason that such users are usually unwilling to devote the time and effort necessary to such training.

Is there a happy medium? The answer in this case is "No" - a half flexible, semi-easy to use system is not the solution. The requirements for flexibility and ease of use must be met by a dual set of capabilities in the system - a limited set of easy to use options for the user interested in standard processes and a more extensive set of flexible options for those involved in unique or original type work.

Some of the specific features of the user language are:

- Fixed field card input of operators and associated parameters
- Free field keyboard input of operators and associated parameters
- Automatic file assignment with an override capability
- Repeat capability for individual operator or series of operators
- Control card editing and error detection
- Real time translation of operators
- Input data editing and reformatting
- Vector input using a graphic pen
- Capability to insert compiler language statements in the job sequence.

The design of the user language has been influenced by experience with the prototype version of IDAPS developed by SDC and an analysis of other systems including VICAR[2], PAX II [4], and the system at Scripps Institution of Oceanography[3].

4.1.2 Programmer Language

The choice of languages used to develop image processing systems has been based on three factors which make the use of any single existing language impractical. These factors are:

- image processing involves a large amount of bit and byte manipulation;
- the interative nature of many image processing techniques requires large amounts of CPU and I/O time thus necessitating extremely efficient code;
- the experimental nature of much of the image processing work to date has fostered the use of universal languages such as FORTRAN and to a lesser extent PL/1.

These factors will continue to influence the development of image processing systems of the future. There is no existing compiler type language that builds optimum code or is machine independent. Machine language assemblers are by definition machine dependent, thus making transferability extremely difficult.

Due to the number and size of the S-056 pictures to be processed and to the interactive nature of the processing, speed is considered the overriding factor dictating the choice of language for the development of IDAPS. This is not to say that transferability will be totally sacrificed for speed, but that in cases where there will be a significant difference in run time between a program coded in machine language and compiler language, assembly language will be used. Significant difference is here defined to be that time lapse which would cause an interactive user of the system to become irritated or discouraged in waiting for the results of his request for processing. For example, a processing time of 4 seconds as opposed to 2 seconds would not be considered significant even though it represents a 100% increase in time, whereas a processing time of 30 seconds as opposed to 20 seconds may be considered objectionable in that studies have shown that waiting time at an interactive console in excess of 20 seconds tends to fatigue and discourage a user.

On a percentage basis it is expected that in excess of 85% of the code produced for IDAPS will be in compiler language - in all likelyhood FORTRAN. Specific areas in which FORTRAN will not be suitable are bit and byte manipulation, fast Fourier transform, I/O control language translation and interactive message handling. In these cases machine language will be used.

4.2 OPERATING SYSTEM INTERFACE

There are three major sets of users of the proposed image processing system:

- the system programmer
- the interactive user
- the off-line user

These users require different sets of capabilities. For example, the system programmer requires a relatively fast turn-around time (1-2 hours), a moderate amount of CPU time for compiling and debugging, a moderate amount of core space, not much disk space, a large amount of standard I/O for compilations, dumps, etc. and very little special I/O. Whereas, the interactive user demands very quick turn-around time, a relatively small amount of CPU time and core space, a moderate amount of disk space to store small images, not much standard I/O, but a high volume of special I/O such as TV, photowriting, hardcopy etc. These requirements are summarized in Figure 4-1.

The interactive user is concerned primarily with experimentation. As techniques are developed, the interactive user will want to run series of tests on various types of images while varying single parameters to establish the effectiveness of the technique. As the system goes into production status, the interactive user will be experimenting with real data to establish such parameters as PSF, MTF, filters, etc.

Off-line use of the system is associated primarily with production type runs where the user knows in advance the sequence of operations that he is going

User \ Requirement for	Fast turn around time	CPU time	Core space	Disk Space	Standard I/O	Special I/O
System Programmer	Medium	Medium	Medium	Low	High	Low
Interactive User	High	Low	Low	Medium	Low	High
Off-line User	Low	High	High	High	Medium	Medium

Figure 4-1. User Requirements

to apply to a series of images. As more and more of the system techniques become proven and users gain confidence in the system, off-line operation will become the predominant mode of operation.

Figure 4-2 summarizes the system utilization from initial system development through production.

Due to the diversity of the system users and to the fact that they may be demanding simultaneous access to the system, a manufacturer provided operating system capable of providing such access in an efficient manner is required. This is not to imply a requirement for multiprocessing, but does suggest some form of time sharing whether it be a multiprogramming or paging scheme.

Several levels of priority are required to provide timely service to the users. The possible priority scheme may be:

- Interactive user - priority 1
- System Programmer - priority 2
- Off-line user - priority 3

In this case the interactive user would receive an immediate response to his comments or requests. During the time that he is thinking of his next action or while his I/O is being handled, the operating system would service the other users based on their respective priority.

Specific functions of the operating system include:

- Interrupt processing
- Task scheduling
- Resource allocation
- I/O control
- Record keeping

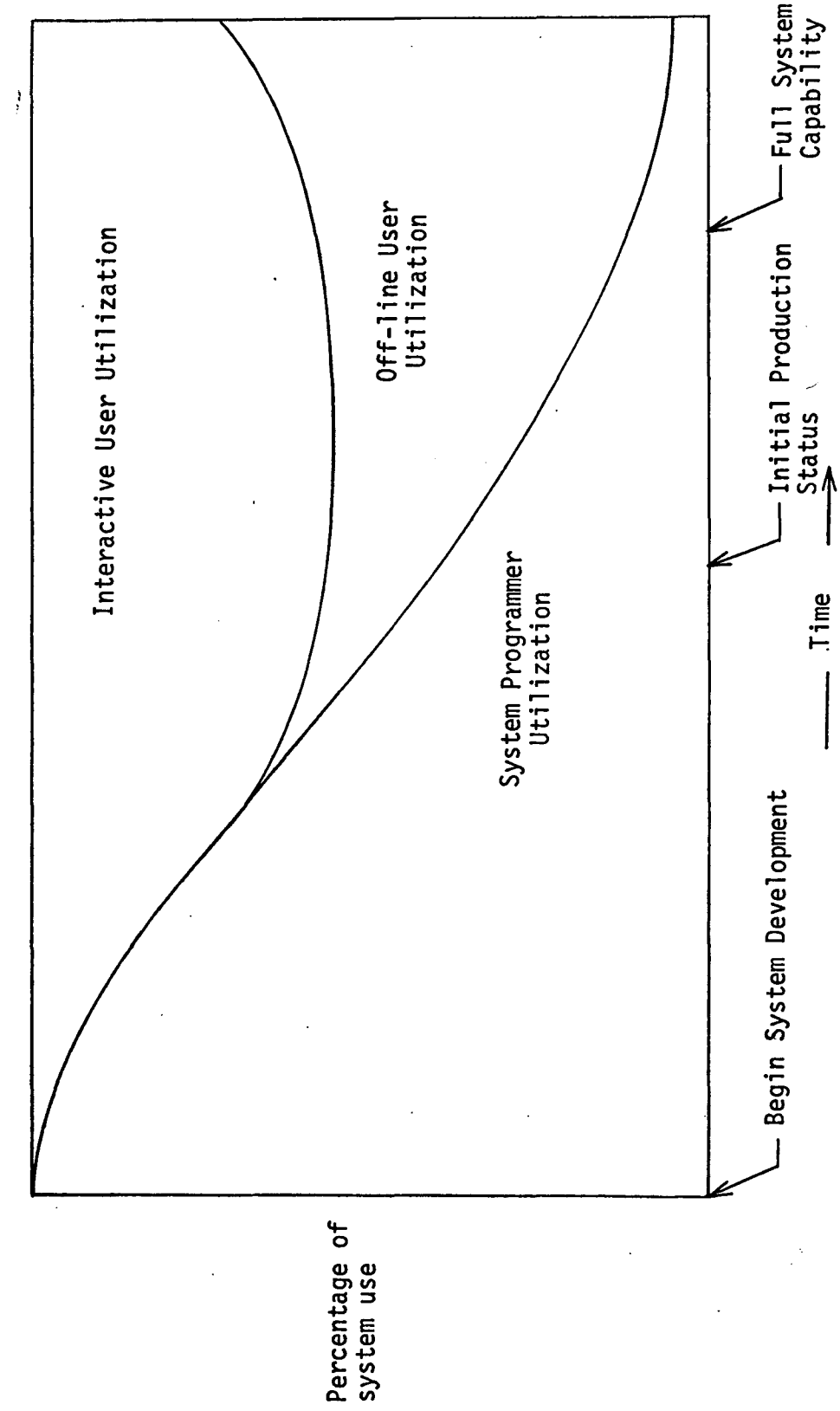


Figure 4-2. System Utilization

4.3 OPERATORS

The operator is the basic tool of the system user. It is through the use of the operators and their associated parameters that the user communicates with the system. To provide the required flexibility, an extensive list of operators is proposed. It should be noted that some operators perform very sophisticated techniques while others perform very simple tasks. Some of the more sophisticated operators actually perform the function of several of the less sophisticated operators, so that there is somewhat of an overlap in the functions of the operators.

This section provides a brief description of the major operators. The list of operators cannot be considered all inclusive since it is realized that new requirements will call for new techniques. The intent here is to outline the basic operators which will provide the user with a set of general purpose image processing tools. Three main classes of operators are discussed in this section:

- Application operators
- I/O operators
- Utility operators

4.3.1 Application Operators

The application operators are designed to modify and/or aid in analyzing images. A major design criterion for building these operators will be to make them easy to use by the experimenter. It should be noted that many, if not all, application operators serve more than one purpose; i.e., they can be used to satisfy the needs of several techniques by changing the input parameters. This is demonstrated by plotting application operators and image processing techniques in a matrix as shown in Figure 4-3.

4.3.1.1 Position Dependent Alter - This operator performs an alteration of the numbers in a picture array of the form $P' = a(r) + b(r)P$ where $a(r)$

Status * Prototype Operational
o Adaptation

Design Objective	Status	Operator	Position Dependent Alter	Non-symmetrical Field Cor.	Invariant Alter	Non-linear Adjustment	Cross Correlate	Multiframe Average	Smoothing (Integrate)	Digital Filter	Fourier Transform	Scale	Convolve	Deconvolution	Differentiate	Transfer Function Generator	PSF Generator	Filter Generator	Edge Modification	Area Fill	Histogram	Color	Classify	Iso-Data Contour	Three Dimensional Projection	Boundary Isolation	Area	Centroid	Growth Rate	Velocity	Picture Difference	Rotate	Translate	Zoom	Register	Perspective Correction	Coordinate Generation	Radiation Intensity	Data Management	Picture statistics
Field Non-uniformity Correction			X	X																																			
Film Non-linearity Correction				X																																			
Scanner Non-linearity Correction				X	X																																		
Geometric Distortion Correction						X																												X					
Film Grain Noise Removal							X	X																										X					
Scanner Noise Removal								X		X	X							X			X																		
Scratch & Blemish Removal																	X			X																			
Compensation for Telescope Optics										X				X			X	X																					
Motion & Jitter Blur Removal										X					X	X		X	X																				
Picture Contrast Improvement				X								X									X																		
Feature Detail Enhancement										X			X			X	X																						
Shadow Reduction										X							X																						
Combination of Multiple Frames								X										X			X	X																	
Global Feature Enhancement									X	X							X																						
Transform Analysis											X	X									X	X		X															
Geometric Analysis					X							X														X	X	X	X	X	X	X	X		X				
Photometric Analysis																					X	X	X				X	X		X						X	X		
Statistical Analysis																					X						X	X								X	X	X	X

Figure 4-3. Application Operator/Design Objective Matrix

and b(r) are correction factors provided by the user in tabular form. The independent variable (r) is the radial distance from the picture element P to the center of the original field of view.

4.3.1.2 Non-Symmetrical Field Correction - This operator corrects for field non-linearities which cannot be expressed as a simple function of the picture geometry. A correction is applied to the elements within a picture array in the form $P' = a(x,y) + b(x,y)P$ where a(x,y) and b(x,y) are two-dimensional correction factor arrays provided by the user and x and y are the vertical and horizontal location of the picture element P. The dimensions of the a & b tables should be small enough for easy handling and large enough to provide an accuracy of correction of at least 1% for a 1024 x 1024 element array.

4.3.1.3 Invariant Alter - This operator adjusts each element in a picture array in accordance with a one dimensional look-up table. The look-up table consists of one entry for each density value produced by the scanner.

4.3.1.4 Non-Linear Adjust - This operator corrects for non-linearities in the scanning process which result when a position dependent scanner, such as the flying spot or image dissector are used. The correction is of the form $P' = F(x,y,P)$ where x and y are the position of the picture element and P represents the original density value of the scanned film (not necessarily a 1:1 relation to the number of scanner output gray values). The number of (x by y) correction tables input by the user depends on the number of possible values that P may assume, but should be kept to a minimum in the interest of processing ease.

4.3.1.5 Cross Correlate - This operator determines the cross correlation function of two input picture arrays. Either a numerical or Fourier approach may be used, depending on the efficiency produced. A two dimensional

table of correlation values is produced as well as a display of the vertical and horizontal translation needed to maximize the cross correlation of one frame with the other.

4.3.1.6 Multi-Frame Average - This operator combines the data from similar picture arrays into one picture array by a modified averaging process. The process used should be tailored to the number of input arrays (n) available as follows:

If $2 \leq n \leq 3$, simply average the n values for each picture element.

If $4 \leq n \leq 10$, compute the average deviation of each n element values, throw out any values which are outside (Q)% of one average deviation and average the remaining values for each picture element.

If $n>10$, compute the standard deviation of the n values for each picture element position, throw out any values which lie outside of 1 standard deviation by more than (R)%, and average the remaining values for each picture element.

4.3.1.7 Smoothing - This operator spatially integrates each element within an array by averaging its eight neighboring elements, comparing the subject element with that average and adjusting the elements which differ from the average of their neighbors by more than a prespecified amount by a second prespecified percentage.

4.3.1.8 Digital Filter - This operator accepts the digital filter arrays produced by the Transfer Function Generator and Filter Generator operators and accomplishes digital filtering in the Fourier domain through the direct manipulation of frequency terms. The input picture will normally be input in the spatial domain although an option should exist to input transformed images. The filter input will be in the frequency domain as magnitude and phase terms, and the output will be a filtered picture.

4.3.1.9 Fourier Transform - This operator applies a fast Fourier algorithm in two dimensions to produce either an m x m array of magnitude and phase frequency terms from a picture array, or conversely, to produce an m x m picture array from magnitude and phase frequency term arrays. The Fourier frequency terms should be arranged in two dimensional arrays with the DC term in the center-most location and highest frequencies at the borders.

4.3.1.10 Scale - This operator redistributes data values between maximum and minimum points in accordance with a prespecified criteria. Specifically, in addition to specifying the maximum and minimum values between which the scaling should be done, the operator should provide for the following scaling curves:

- Linear
- Logarithm
- Cube Root
- Square Root
- Square
- Scaling for distributing phase terms into gray values (360° $\Longrightarrow$ 60 gray levels)

An option should be provided to either set values outside the max/min limits to those limits or to zero.

4.3.1.11 Convolve - This operator provides the capability for convolving one n x n array with another m x m array to produce an ((n+m) x (n+m)) output array. An option for providing the input arrays in either the spatial domain or frequency domain should be provided as well as for specifying the size of the output. If the output array size is larger than either of the input arrays, both inputs should be padded with a border of zeros up to that size. An option should be provided for surrounding one or both inputs with a border of zeros sufficient to make n + m equal to the specified output array size.

4.3.1.12 Deconvolve - This operator employs the Fourier technique of inverse filtering to deconvolve an input array with a point spread function (PSF). Frequency terms of the picture array are divided by the frequency terms of the PSF and the inverse transform is computed. Capability for accepting input arrays in either the spatial or frequency domains should be provided as well as for limiting the amount of correction applied to any frequency term. An option for modifying the frequency terms of inverse filter through the interactive experimenter's console is necessary. This can be accomplished by providing a display of the two-dimensional frequency terms of the inverse filter and by using the graphic pen to specify sets of frequency terms to be altered prior to applying the filter to the picture transform.

4.3.1.13 Differentiate - This operator computes the spatial derivative of an image array in a prespecified direction on the array. The approach may employ either numerical or transform methods to increase efficiency and should make provision for specification of the direction for differentiation from the interactive experimenter's console.

4.3.1.14 Transfer Function Generator - This operator provides a quick and easy means for assembling an array of numbers from any of a number of predefined transfer functions. The input to this operator is the specification of all variables in the function through either the interactive experimenter's console or, if operating in a batch mode, through punch cards. The output is an array of numbers which can be applied to a picture by the Digital Filter operator to perform desired filter operations. This operator includes the capacity for specifying any of a number of different roll-off curves to smooth the filter at its edges.

4.3.1.15 PSF Generator - This operator provides the capability for generating complex, non-symmetrical, three-dimensional functions for use in the Deconvolution operation. The graphic pen is used to specify an arbitrary shape to define the boundary of the base of the function, and a side profile which dictates the shape of the surface above the base. The two dimensional array of numbers produced by this operator should be normalized to make all values fall between 0-100.

4.3.1.16 Filter Generator - This operator provides a means for generating customized two dimensional filters for use in conjunction with the Digital Filter operator. The user should be able to define the locus of half power points on a two-dimensional frequency plane for either high pass, low pass, or band pass/reject types of filter. Additionally, the user should be able to specify any of a number of standard rolloff profiles through use of the graphic pen.

4.3.1.17 Edge Modification - This operator applies an edge attenuation or "Window" function to an array of numbers to eliminate or reduce the discontinuities in the spatial domain which may cause problems in the frequency domain. The user should be able to apply pre-stored standard functions, such as the cosine bell, or to "draw" a non-standard function with the graphic pen. The net effect of this operation should be to "feather" the edges of a picture.

4.3.1.18 Area Fill - This operator provides a means of determining the "inside and outside" of a closed contour. Given an array of "1"s and "0"s, where the border of an irregular, closed contour is represented by "1"s and the surrounding and interior area are "0"s, this operator identifies those elements within the contour and sets each of them to "1". A feature should be provided to combine the output of their operator with a picture array by replacing the elements in the picture array with a pre-specified number wherever there is a "1" in the Area Fill array.

4.3.1.19 Histogram - This operator calculates the frequency of occurance of conditions within a data set and produces a two-dimensional histogram for graphic display or hardcopy plot. The histogram is based on numbers from within a full picture array, along a prespecified line, or within some prespecified irregular contour.

4.3.1.20 Color - This operator reformats input data to provide color displays on the interactive experimenter's console. An option for selecting and applying any of several most used color schemes to one or more frames of data should be provided as well as for applying specific colors to specific data values on an ad hoc basis.

4.3.1.21 Classify - This operator applies a pattern recognition classifier to a data set to recognize and categorize specific characteristics of the data. Data input is normally in the form of three or more data arrays where each array corresponds to a band of spectral energy. This operator should be "trainable" so that by providing calibration data along with an identification tag, the operator is "trained" to subsequently recognize similar occurances in the data.

4.3.1.22 Iso-Data Contour - This operator produces iso-data contour maps from input arrays where each contour represents some pre-specified range of data values and outer boundaries of the contours are delineated by a line profile. The ability to specify the range of data values to be grouped within a contour gives flexibility in determining the number of profiles produced within the map. Output is either on graphic display or hard copy plot.

4.3.1.23 Three Dimensional Projection - This operator accepts an array of numbers and produces a perspective line drawing in three dimensions as its output. Output should be provided on either graphic display or hardcopy plot.

4.3.1.24 Boundary Isolation - This operator resembles the Iso-Data Contour operator except that the user simply specifies a single threshold value in the input data set and this operator locates and produces a line drawing of the border of areas above and below that threshold. Output should be on graphic display or handcopy plot.

4.3.1.25 Area - This operator uses the output of the Boundary Isolation or Area Operators, or accepts boundary definition from the interactive experimenter's console to calculate the real or relative area within a boundary. In calculating real areas, the assumption is made that all necessary corrections for aspect ratio and geometric distortion have been accomplished. Relative areas are in terms of the number of picture elements contained in the area.

4.3.1.26 Centroid - This operator locates the centroid of any area within a data array with respect to the upper left corner of the array. The subject area may be provided by the Area Fill or Boundary Isolation operator or directly from the interactive experimenter's console.

4.3.1.27 Growth Rate - This operator uses two arrays of data from the Area operator and calculates the rate of growth of the area relative to the actual time elapsed between frames and in terms of real or relative areas. The time elapsed between frames must be provided by the user.

4.3.1.28 Velocity - This operator calculates the rate and direction of movement of a point from its position in one input array to its position in a second. These points may be provided by the user through the interactive experimenter's console, or automatically by some operator such as Centroid. The time elapsed between frames must be specified by the user. Output velocity is in real or relative terms and direction of motion is in degrees from the three o'clock position.

4.3.1.29 Picture Difference - This operator subtracts one array from a second, normalizes the result, and either prints the resulting values or displays them as a picture.

4.3.1.30 Rotate - This operator rotates a picture array about some pre-specified point through some pre-specified angle. An option is provided to store the output array as a larger dimension array or to truncate those portions which fall outside the bounds of the original array.

4.3.1.31 Translate - This operator shifts an input array vertically or horizontally through some pre-specified distance (not necessarily an even number of picture elements). An option is provided to present the output as a larger array than the original, or to truncate those portions which fall outside of the original dimensions.

4.3.1.32 Zoom - The Zoom operator allows the user to uniformly shrink or expand the scale of an image array. This is done by irregularly fracturing the picture over its surface and adding additional picture elements at the fracture points through interpolation, or by simply reducing the number of elements by interpolation of new points. An option for specifying the desired adjustment with a simple magnification factor or by identifying a line segment in the before and after versions is required. If the picture is enlarged by Zoom, an option should exist to truncate any area which falls outside the original array size or to automatically increase the size of the array by an appropriate magnification factor.

4.3.1.33 Register - This operator employs a geometric "rubber sheet" algorithm to perform non-uniform geometric adjustments on an image array. The desired adjustments are specified by locating reference points in the "before" and "after" arrays. These points roughly define rectangles

which are used to determine the amount of vertical or horizontal stretch or shrink required in a localized area of the picture array. Up to 100 pairs of these reference points may be used in defining the geometric operations needed to register two frames of image data.

4.3.1.34 Perspective Correction - This operator applies a geometric adjustment in one direction to an image array to correct the perspective distortion produced when a surface is viewed at an angle. An option of simply specifying the angle of perspective and the axis of rotation or of locating the upper left corner of the array with respect to the solar coordinates is provided.

4.3.1.35 Coordinate Generation - This operator calculates the location of the solar poles and equator and provides any of a number of standard mapping coordinates to an image array as an overlay. Where less than the full solar disk is displayed, the location of the upper left corner of the array must be provided. Pointing and timing information must be provided by the user in order for the operator to make the necessary calculations. An option for obtaining the coordinate position of any picture element on a full solar image is also provided.

4.3.1.36 Radiation Intensity - This operator computes the total energy produced by a solar feature per unit of time or provides the radiation intensity at any pre-specified point. It assumes that all radiometric corrections have been made to relate data values to radiation intensity, and that the time of exposure of the data frame is provided by the user. The area over which total flux is calculated is provided as an output from the Area Fill operator.

4.3.1.37 Data Management - This operator provides the function of a standard data management system by providing the user with a means to store and retrieve pertinent information about the experiment. Through this operator the user

may identify an image frame or series of frames by specifying key features of interest. By referencing the frame number the user may obtain pertinent information about the conditions under which it was recorded and other related information.

4.3.1.38 Picture Statistics - This operator accepts a frame of image data and calculates the statistical properties of the whole frame or any portion of the frame specified by the user. The ability to compute the sum, mean, variance, average deviation and standard deviation of array values and to provide such information as the maximum and minimum values within the data set or the value of a specific element is required. A capability for producing a plot of data values along a line within an array is also required.

4.3.2 I/O Operators

Input/output is a major component of an image processing system. Digitized images, operating instructions, parameters, curves, etc. must be input. Output includes CRT images, hardcopy images, plots, histograms, movies, vectors, etc. This section provides a brief description of the major I/O operators.

4.3.2.1 Read Scanner Data - Reads the output of the scanner(s), converts the data to computer format, and creates a file on disk storage.

4.3.2.2 Read Graphic Pen - Reads the output of the graphic pen, performs the necessary thinning to minimize data points in a vector and creates a table of X,Y coordinates.

4.3.2.3 Assign File - Creates an entry in the file table for the identified file and reserves space on disk for its storage.

4.3.2.4 Copy File - Copies a file from disk to core, core to disk, disk to tape, tape to disk, tape to tape, etc.

4.3.2.5 Print - Prints an array or portion of an array in integer (gray scale), floating point, bilevel or overprint format.

4.3.2.6 Label - Inserts printed labels on a frame of data.

4.3.2.7 Plot - Plots three dimensional projections of image data arrays.

4.3.2.8 Write Photowriter Data - Converts data from computer to photowriter format and outputs the image.

4.3.2.9 Write CRT Data - Converts data from computer to CRT format, stores on refresh memory and initiates the output to the CRT.

4.3.2.10 Resolution Chart - Generates a resolution chart.

4.3.2.11 Frame Mask - Generates a mask to include border, gray scale step wedges, labels, tic marks or grid, and histogram of gray scale distribution to aid in identification, analysis and documentation of images.

4.3.2.12 Multiple Display - Provides the capability of combining multiple frames of data into a single frame for display purposes.

4.3.2.13 Movie - Generates a movie of a series of frames by providing the necessary sequencing and registration of frames.

4.3.2.14 Extract - Extracts a portion of a frame of data based on a beginning X,Y coordinate and the size of the desired array.

4.3.2.15 Insert - Inserts an array of data into a larger frame.

4.3.2.16 Vector - Inserts a vector or series of vectors on a frame of data.

4.3.3 Utility Operators

The utility operators are designed to provide a capability of controlling system operation, performing elementary mathematical operations and to provide diagnostic aids.

4.3.3.1 Integer to float - Converts an array of data from integer to floating point format.

4.3.3.2 Float to integer - Converts an array of data from floating point to integer format.

4.3.3.3 Magnitude/Phase to Real/Imaginary - Converts an array of data from magnitude/phase to real/imaginary.

4.3.3.4 Real/Imaginary to Magnitude/Phase - Converts an array of data from real/imaginary to magnitude/phase.

4.3.3.5 Add - Adds corresponding elements of two or more frames of data or adds constant to each element.

4.3.3.6 Subtract - Subtracts one frame of data from another, element by element or subtracts constant from each element.

4.3.3.7 Multiply - Multiplies corresponding elements of two frames of data together or multiplies each element by a constant.

4.3.3.8 Divide - Divides one frame of data by another or divides each element by a constant.

4.3.3.9 Normalize - Reduces the value of each element of an array so that the sum of the resulting elements equal 1.

4.3.3.10 Size - Specifies the size of an image array.

4.3.3.11 Comment - Provides capability to insert instructions or documentary comments in run stream.

4.3.3.12 Dump - Provides dump of selected portion of a frame of data.

4.3.3.13 Interactive Mode - Places system in the interactive mode.

4.3.3.14 Batch Mode - Places system in the batch mode.

4.3.3.15 Tutorial Mode - Places system in the tutorial mode of operation so that detailed instructions are printed to the interactive user.

4.3.3.16 Flip - Flips an array of data about the major diagonal, minor diagonal, vertical axis or horizontal axis.

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APPENDIX A

1. TECHNIQUE OBJECTIVE
(Name)

FIELD NON-UNIFORMITY CORRECTION

2. PURPOSE
(Origin & nature of the problem addressed)

The failure of the S-056 telescope to record a uniformly illuminated flat field as a constant density film frame is a form of vignetting which must be corrected.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

a) Apply a correction $P' = a(r) + b(r)P$ where $a(r)$ and $b(r)$ are correction factors which are functions of the radial distance (r) of the element P from the center of the field. a and b are input as one dimensional look-up tables.

b) Apply a correction $P' = a(x,y) + b(x,y)P$ where $a(x,y)$ and $b(x,y)$ are correction factors which are functions of the verticle and horizontal position of the element P in the field of view. a and b are input as two dimensional look-up tables.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

Analysis of test results are needed to determine the extent of the field non-uniformity, and to develop the look-up tables needed for correction.

1. TECHNIQUE OBJECTIVE
(Name)

FILM NON-LINEARITY CORRECTION

2. PURPOSE
(Origin & nature of the problem addressed)

The ability of photographic film to record the intensity of electromagnetic radiation as a function of film density is an non-linear relationship. In order to adjust the recorded data to reflect radiation intensity values, a non-linear correction must be applied.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

Film curve correction should be made from a correction look-up table which relates the measured film densities to radiation intensities.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

The film characteristic curve for S-056 flight film must be accurately determined for all conditions of film exposure, storage, and development. Accurate sensitometry must employ highly calibrated sources of radiation in the spectral wavelengths in which the telescope will operate.

1. TECHNIQUE OBJECTIVE
(Name)

SCANNER NON-LINEARITY CORRECTION

2. PURPOSE
(Origin & nature of the problem addressed)

The process of extracting information from recording film involves the determination of the relative density of the film as a function of position. Since this measurement is accomplished by determining the amount of light transmitted through the film at different positions (a non-linear process), data linearization is required.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

a. Assume that the scanner is position independent. The correction to be applied could then be expressed in a two dimensional table of (n) values where n corresponds to the number of gray levels measured by the scanner. The correction is then F(n) which is an intensity value obtained by analytic measurement.

b. If the scanner is position dependent, as might be expected from image disector or flying spot scan devices, the correction must be applied as a function of three dimensions F (x,y,n) where n is again the measured gray scale value and x and y denote the position of the measured value in the field of view.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

Calibration data is required to completely define the conversion characteristics of the scanner. These data might be obtained from the scanner manufacturer or by scanning a number of known, constant density fields, covering the useful density range of the instrument.

1. TECHNIQUE OBJECTIVE
(Name)

TELESCOPE GEOMETRIC DISTORTION

2. PURPOSE
(Origin & nature of the problem addressed)

Geometric non-linearlity is a common characteristic of photo-optical devices. The S-056 telescope is expected to exhibit a considerable degree of geometric distortion. This distortion may be manifest in a common "pin cushion" or "barrel" distortion or in a much more irratic and unpredictable form. Also, the projection of the spherical solar surface on the film plane severely distorts perspective at the edges of the solar disk.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

In correcting for the geometric properties of an image, two factors are of concern - the method of describing the corrections to be applied, and the method of calculating the correct value for each picture element in the output array.

A. Input Description

1. Assume that the distortions introduced by the telescope are described by a relation $(\Delta\ )' = f\ (r, \Delta x)$ where (Δx) and $(\Delta x)'$ are unit lengths in the "before" and "after" arrays and r in the radial distance of Δx from the center of the field of view. $f(r,\Delta x)$ must be determined analytically.
2. Identify input and output rectangles which describe the desired correction. A number of such rectangle pairs may be used to describe complex geometric operations (this approach has been applied extensively by JPL in their GEOM operator.

B. Determination of correction values

1. Simply use the picture element in the input array which is closest to the desired location identified by the input description.
2. Interpolate between surrounding values to determine the picture value for the location indicated by the input description.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

A determination must be made of the degree and nature of the geometric distortion of the S-056 telescope. Two approaches are suggested -

a. Analyze the relative positions of identifiable reference points on known geometric patterns.

b. Compare photographs of known shapes (such as the solar limb) to determine distortions in the original and the recorded images.

1. TECHNIQUE OBJECTIVE
(Name)

FILM GRAIN NOISE REMOVAL

2. PURPOSE
(Origin & nature of the problem addressed)

Photographic film is a discrete recording device in that the individual film grains are photo-chemically darkened during the photographic process. When a scanning microdensitometer with a spot size that approaches the film grain size (< 1 micrometer) is used to extract data from film, random variations are introduced into the data. This film grain noise must be reduced to an acceptable level if certain subsequent image processing operations are planned.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

Multiple frames of the same object must be averaged in the computer to improve the S/N ratio. To do this it is first necessary to register the frames so that identical objects in each frame are located at the same space reference. This requires a cross correlation of several reference points frame-to-frame and the geometric adjustments (translation/rotation) needed to maximize the correlation of the frames. Once registered, averaging of corresponding points is accomplished by checking the variation of individual points from the computed standard distribution, throwing out any "wild" values and averaging those which remain.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

Multiple frames must be taken by the S-056 camera within a relatively short time period (five minutes or less). The more frames available for averaging, the better the signal to noise figure that can be obtained by this technique.

1. TECHNIQUE OBJECTIVE
(Name)

SCANNER NOISE REMOVAL

2. PURPOSE
(Origin & nature of the problem addressed)

A number of factors may contribute to the introduction of noise in the film scanning process - random noise such as photomultiplier "Shot" noise and periodic noise which may originate from poorly filtered power supplies or from inductive coupling with other ac circuits. Mechanical imperfections in mechanical scan devices can introduce periodic noise. Even the basic action of scanning a picture at a discrete number of points instead of continuously causes a distortion in the data which may be classed as noise.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

a. A multi-frame averaging technique may be useful in reducing the effects of random scanner noise. In this application, however, the process is much simpler than when averaging for film grain or stray radiation noise removal since the multiple frames may be generated by successively scanning the same film a number of times. This means that little or no registration is required and only one picture frame is necessary.

b. Periodic noise may be reduced by applying a digital "notch" filter at all points in the spectrum where the periodic noise exists. Location of such noise points in the spectrum is sometimes difficult and a "cut and try" approach may be necessary.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

Multiple scans of a picture are needed for method "a" above. These should be prepared by sucessively scanning the subject picture a number of times with no disturbance of the geometric position or the scanner between each scan.

1. TECHNIQUE OBJECTIVE
(Name)

SCRATCH & BLEMISH REMOVAL

2. PURPOSE
(Origin & nature of the problem addressed)

S-056 flight film is a special film developed by Eastman for the recording of soft x-rays. It is extremely prone to scratching, and because of a special "Remjet" backing may be contaminated with small opaque particles after film processing is complete. It is desirable to replace such scratches & blemishes with an approximation of the original data in order to carry out subsequent image analysis operations.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

The removal of scratches & blemishes is a two step process - location of the anomolies, and anomoly removal.

a. Location of film scratches or blemishes must, in the final judgement, be made by a trained observer. Although such support algorithms as edge profile plotting, spatial gradient analysis, and gray scale thresholding are important, it will be necessary for a skilled observer to indicate to the computer which features in a picture are anomlies and should be removed.

b. Removal of scratches and blemishes will generally be a process of extrapolation or interpolation -

- extrapolation from the edges for large, roughly circular blemishes
- interpolation across narrow scratches (this requires that each interpolation path be calculated as the normal to the long dimension of the scratch)

Extrapolation is much the simpler of the two and appears to be adequate for the purposes of S-056.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

A method for displaying areas of a picture and for quickly indicating boundaries to the computer is essential. A CRT display equipped with a graphic input device such as a track bell or graphic pen is recommended.

1. TECHNIQUE OBJECTIVE
(Name)

COMPENSATION FOR TELESCOPE OPTICS

2. PURPOSE
(Origin & nature of the problem addressed)

The S-056 telescope produces a rather severe blur as an inherent characteristic of its glancing incidence optics. The use of film as a means for recording image data introduces further blur and loss of high frequency. It is desirable to reduce the effects of telescope blur and to improve the overall high frequency content of the pictures.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

Two Fourier transform techniques are applicable to the reduction of blur and the improvement of overall high frequency content in S-056 photographs -

a. Digital filtering may be used to improve the response of telescope optics by amplifying high frequencies to improve the optical transfer characteristics of the telescope. The success with which this may be accomplished depends on the signal to noise characteristics of the original picture.

b. Deconvolution, which is a form of digital filtering, attemps to reverse the effects of optical blur by reversing the mathematical process which takes place in the Fourier domain. The basic principles of deconvolution are explained in section 3.1 of SDC TM-(L)-HU-033/005/00.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

In order to compensate for telescope blur, it is important to obtain an accurate description of the losses incurred. A common measure is the MTF of the system, but a more descriptive function is the optical point spread function. A number of methods for obtaining the system PSF are discussed in Section 3.2.4 of SDC TM-(L)-HU-033/005/00.

1. TECHNIQUE OBJECTIVE
(Name)

PICTURE CONTRAST IMPROVEMENT

2. PURPOSE
(Origin & nature of the problem addressed)

Correct exposure values for the S-056 telescope are very difficult to predict and it is highly likely that film exposures will be made in such a way as to produce very low contrast photographs. Although nothing can be done to retrieve image data that is lost due to incorrect exposure, contrast improvement techniques are needed to assist the observer in the visual analysis of the photographs.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

Two approaches are suggested for contrast improvement. Both assume that some analysis has been made of the subject photograph to determine the range of gray values in which the bulk of the valid picture data resides. Gray scale histograms are valuable for this analysis.

a. An automatic scaling may be applied in which an upper and lower limit is specified, and the data in between is scaled along some curve to achieve a contrast "stretch."

b. A one-dimension table of correction values may be used for a more precise adjustment of gray values at the expense of ease-of-use of the technique.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

A gray scale histogram plotting % of occurance for each gray value is needed in the analysis prior to the application of this technique.

1. TECHNIQUE OBJECTIVE
(Name)

FEATURE DETAIL ENHANCEMENT

2. PURPOSE
(Origin & nature of the problem addressed)

Because of the blurring effects of the photo-optical system of the S-056 experiment, picture detail will be highly attenuated. Although compensating for telescope optics through deconvolution should improve detail to the maximum amount within the limits dictated by the picture S/N ratio, a more general high pass filtering technique is needed for those cases where determination of the telescope PSF is difficult or impossible.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

Digital filtering, accomplished in the frequency domain, should be applied to amplify high frequency data to a limit dictated by the S/N ratio. The roll-off characteristic of the filter should be tailored to the picture data to reduce the effects of ringing or spurious images.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

Some knowledge of the spectral density of the noise in the subject photograph is valuable. Otherwise, it will be necessary to make a series of runs to determine where the high frequencies become noise dominated.

1. TECHNIQUE OBJECTIVE
(Name)

SHADOW REDUCTION

2. PURPOSE
(Origin & nature of the problem addressed)

Quite often portions of an image frame lie in a darkened region or shadow. When this happens, picture detail within that shadow may be difficult to observe. A technique to reduce the effects of shadow in S-056 images will be valuable in their visual analysis.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

The approach for shadow reduction is much the same as for detail enhancement except that a digital band-reject filter is applied in the frequency domain to attenuate the low frequency components which constitute the picture shadow data. Again, the roll-off curve should be designed to minimize the impact on the remaining picture detail.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

No Special Requirements.

1. TECHNIQUE OBJECTIVE
(Name)

COMBINATION OF MULTIPLE FRAMES

2. PURPOSE
(Origin & nature of the problem addressed)

Experiment protocol for S-056 calls for series of pictures to be made through various filters at different rates. Since the eye can only observe image data on a single frame at a time, the ability to combine data frames into a single picture would be valuable.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

A number of approaches might be applied to combine multiple frames into a single picutre:

a. Straightforward averaging of corresponding picture elements.

b. Assignment of each frame to a different color and then varying the color intensity with respect to the gray value in the original frame.

c. Using a multi-frame classifier to produce a two-dimension classification plot containing the vital information from several frames.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

Before any frame combination technique is applied, all frames must be registered so that corresponding points in each frame are superimposed on each other.

1. TECHNIQUE OBJECTIVE
(Name)

GLOBAL FEATURE ENHANCEMENT

2. PURPOSE
(Origin & nature of the problem addressed)

Sometimes picture detail or noise distracts the observer to a point where he "cannot see the forest for the trees". When this happens, it may be helpful to slightly blur the picture to eliminate some of the distracting high frequency data. A technique is needed to provide a controlled amount of picture blur for this purpose.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

Two approaches are suggested:

a. Simple averaging of each picture element with some portion of the value of its neighbors will effectively blur a picture. The amount of blur is controlled by the "weights" which are assigned to determine how much the neighbor contributes to the average, and by the number of neighboring elements that are included in the averaging process.

b. A digital low pass filter may be applied in the frequency domain if more precise control over the blurring process is needed at the expense of processing complexity.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

No Special Requirements.

1. TECHNIQUE OBJECTIVE
(Name)

TRANSFORM ANALYSIS

2. PURPOSE
(Origin & nature of the problem addressed)

Information may often be extracted from image data by analyzing its frequency terms instead of its normal spatial characteristics. Techniques are needed for providing S-056 images in the frequency domain in a form suitable for visual analysis.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

The most useful form for observing pictorial data in the frequency domain is the magnitude and phase components instead of the real and imaginary forms. Because such frequency terms geneally vary over a wide range of magnitude values, a method for scaling magnitude terms to fit within available display equipment is needed. A number of presentation schemes are useful for viewing frequency domain displays:

- Ordinary gray level displays
- Pseudo-color
- 3-D projections
- Iso-data plots
- Histograms

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

No special requirements.

1. TECHNIQUE OBJECTIVE
(Name)

GEOMETRIC ANALYSIS

2. PURPOSE
(Origin & nature of the problem addressed)

The ability to measure the various geometric properties of the S-056 images of the sun is of highest importance to the successful processing of data from the experiment. All of the techniques of Linearization, Noise Removal, Blur Removal, and Enhancement are aimed at providing imagery of suitable quality for this and other forms of analysis.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

A number of geometric characteristics must be measured by the S-056 image processing system in satisfying this objective:

- The system must be able to accurately determine the boundaries of specific features on the solar image.
- The system should provide a semi-automatic means for locating the solar poles and equator and for overlaying solar map coordinates.
- The system must be able to measure the following characteristics of solar features - area, growth rate, centroid, velocity of centroid movement, and velocity of the leading and trailing edge of the feature.
- The system should provide a means for determining the difference between two frames of imagery.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

An interactive, graphic terminal is necessary in satisfying the above requirements. Of particular necessity is the ability to display gray-level images and to manipulate the image data and control the geometric analysis operations with a graphic input device.

1. TECHNIQUE OBJECTIVE
(Name)

PHOTOMETRIC ANALYSIS

2. PURPOSE
(Origin & nature of the problem addressed)

The ability to measure the radiographic properties of the sun through the analysis of S-056 photographs is important to the successful processing of the experiment data. To do this, a number of interrelated capabilities are required.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

Most of the operations which must be designed to support geometric analysis find use in support of photometric analysis as well. Several additional operations are required to satisfy these design objectives -

- Iso-data plots are required to provide "contour maps" of the energy level distribution on the sun. Bands of radiation intensity are grouped together and presented as a multi-line contour map.
- Radiation intensity measurements must be made to determine such things as the level of radiation at specific points, the rate of energy generation from specific solar features or from a unit area within such a feature and the total energy generated within specific spectral bands.
- An automatic classifier should be provided to automatically classify radiation conditions into predefined classes. This operation will be useful in associating radiation patterns with other solar data.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

The same display and control hardware must be provided for satisfying these design objectives as required for the Geometric Analysis objectives.

1. TECHNIQUE OBJECTIVE
(Name)

STATISTICAL ANALYSIS

2. PURPOSE
(Origin & nature of the problem addressed)

The volume and diversity of the scientific data produced by the S-056 experiment can easily overwhelm available researchers. In order to reduce the impact of such a data handling work load and to improve the speed and efficiency with which it may be analyzed, certain statistical tools are required.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

The system should provide the following statistical capability:

- Compute properties such as sum, mean, variance, and standard and average deviation of the numbers within an array or some area within the array.
- Provide data plots of numbers along a line within an array.
- Provide histograms of numbers within an array or within some area within the array.
- Display pertinent statistical information such as the maximum or minimum values within an array or portion of an array and the value of specific points within an array.

Additionally, a data management system must be provided to enable researchers to retrieve statistical information about the S-056 experiment and to identify data frames which satisfy desired sets of descriptive and statistical properties.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

A hardware means for indicating to the computer the areas lines and points of reference within a data array as indicated above, and a means for generating real time and hardcopy plots and printouts of statistical data is required.

1. TECHNIQUE OBJECTIVE
(Name)

MOTION & JITTER BLUR REMOVAL

2. PURPOSE
(Origin & nature of the problem addressed)

Although the Apollo Telescope Mount incorporates a highly sophisticated painting and control system, the possibility does exist that sufficient motion and vibration will be transmitted to the S-056 telescope to degrade image quality significantly. Corrective techniques are needed to reduce the effects of motion and jitter on the image data quality.

3. METHODOLOGY - Alternate Approaches
(List all applicable approaches for solving the problem & discuss the pros and cons of each)

Linear motion and jitter are two different processes and hence, require different corrective approaches.

a. Linear Motion removal has been investigated extensively by Harris, et. al. (reference) and two approaches have been successfully used for removal of motion blur - inverse filtering in the Fourier domain and differentiation in the direction of motion.

b. Jitter removal is a much more complex process, but can be approached in the frequency domain by the application of inverse filters derived from a zero order Bessel function or analytically from a model of the vibrating system.

4. SPECIAL REQUIREMENTS
(For each of the above methods, describe required special hardware items, software, and outside support)

Linear motion removal requires an accurate knowledge of the direction and extent of travel of a point in the image during the time of exposure. Since these factors may not be known, our iterative process may be required with an evaluation of trail results. A priori knowledge of the ATM system jitter may be required to restore images degraded by serious vibration. Since vibration characteristics in space may not be predictable, the measurement of the effects of jitter on a sharp edge may give important clues to the nature of the required corrective filter.